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THERMAL ENERGY STORAGE HEAT EXCHANGER

TOPICAL REPORT

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16. Abstract This report presents sizing procedures for latent heat thermal energy storage systems that can be used for electric utility off-peak energy storage, solar power plants and other preliminary design applications. The methods were developed in a one year study of electric utility energy storage which is documented in CR 135244 "Thermal Energy Storage Heat Exchanger."					
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FORWORD

The material in this report was prepared by the Grumman Aerospace Corporation with main subcontract support from the electric utility engineering and architectural firm, Burns and Roe, Inc.: Messres Robert Vondrasek and Chris Mallner of Burns and Roe, Inc., performed the plant thermodynamic analysis and prepared the installation layouts and cost summaries. Drs. Alina Borucka and George Janz provided consulting on the properties of salts and aided in the selection of specific salt eutectics for this application. The Contract Technical Manager at NASA Lewis Research Center was Mr. Joseph Joyce. The authors wish to extend our appreciation to the above personnel for their valuable contributions.

SECTION 1

INTRODUCTION AND SUMMARY

The NASA Lewis Research Center, in conjunction with DoE, has been exploring the potential for storing thermal energy in the phase change of salts. Grumman recently completed a ten month study as part of this effort, specifically to investigate the feasibility of storing excess thermal energy in the latent heat of salts during the off-peak hours of electric utility plants which could then provide energy to meet peak requirements. To be competitive, the total thermal energy storage (TES) system cost must be less than the cost of increasing plant capacity. The physical characteristics and operating thermodynamics of five power plants, representing contemporary utility designs were defined and locations for integrating TES into each were assessed.

Alternate storage concepts were considered, including:

- tube/shell (baseline)
- intermediate pumped metal loop
- heat pipe
- micro- and macro-encapsulated and bulk PCM.

It was concluded that tube/shell and intermediate pumped metal loop systems, used either to augment feedwater heating or as an energy source for an auxiliary power cycle, required the least development for utility applications. Even though the designs were not optimized, we showed that a salt TES system could provide nearly 7 percent of the peak power required by a typical 525 MW power plant (Ft. Martin, located in West Virginia) at a lower cost than increasing plant capacity. Results of this study are thoroughly documented in Reference 1.

This report presents analytic techniques for initial sizing of a tube/shell or pumped metal loop TES system abstracted from Reference 1. It is assumed that the total quantity of energy to be stored and supplied (KWH), and the usage and storage temperature levels are known.

A general discussion of salt characteristics, properties and costs are presented so that selection of a salt, or salts, can be made. Analytical methods for determining salt quantities, tube spacing and TES module size are reviewed. A description of the baseline tube/shell and pumped metal loop system provides sufficient material for the user to select the appropriate concept for his application. Overall system considerations such as controls are also discussed. Since economics will play a major role in any TES selection process, a thorough discussion of system costs is presented to assure that the potential user does not overlook significant parameters. The report concludes with an illustrative example taken from Reference 1 describing the sizing procedure for an electric utility heating case, demonstrating the step-by-step analytical procedure to be followed.

SECTION 2

REQUIRED SYSTEM DATA

Before a designer can size a TES system he must initially define the overall system requirements. This document assumes that the user can specify certain required system sizing data. This assumption allows the methods presented here to apply to a range of TES situations.

2.1 ENERGY STORAGE AND DUTY CYCLE REQUIREMENTS

The user must first define the total energy to be stored and re-supplied (KWH), and the storage and usage period (hours) for the specific application. The energy storage (KWH) determines the quantity of phase change material required. Extended storage periods have a second order effect on salt quantity by increasing the requirement due to heat loss from the system. Duty cycles are important since they determine the heat storage and removal rates which size the heat exchanger surface area and spacing in the salt.

2.2 SYSTEM FLUID CONDITIONS

In general, a latent heat TES system will be comprised of a salt module, or modules, which will store and re-supply energy to a fluid loop. For example, a TES system used to provide part of the feedwater heating requirements of a power plant can be charged by steam directly from the boiler and can deliver this stored energy to the feedwater during usage periods. Available inlet temperature and pressure, as well as the outlet temperature or range of acceptable temperatures must be defined. The complexity and cost of a TES design will increase with increasing temperature and pressure levels.

SECTION 3

SALT SELECTION PROCEDURE

In general, thermal energy can be stored as either sensible or latent heat. Sensible heat involves the storage of energy by raising the temperature of the storage media, thereby increasing the internal energy of the substance ($mc_p \Delta T$). Typically, solids (metals, salts, etc.) exhibit specific heats of about .2 BTU/lb $^{\circ}$ F so that in order to store 100 BTU in a pound of material, a temperature increase of 500 $^{\circ}$ F would be required. Latent heat involves the storage of energy due to a phase change (e.g., from solid to liquid) of the storage material. For pure salts and eutectic mixtures this transformation occurs at a constant temperature. Salts typically exhibit a latent heat (ΔH_{fs}) of 100 BTU/lb so that in order to store 100 BTU, a pound of PCM would also be required. A major advantage of latent heat storage, however, is that the process can store and re-supply heat at nearly constant temperature, which is necessary when storage and usage temperatures are similar. In this case the amount of storage material required is significantly less with latent heat systems than sensible storage concepts.

3.1 CANDIDATE SALTS

In our case, the total TES system cost was compared with the cost of adding additional power plant capacity. A simplified economic evaluation indicated that the total TES system cost must be less than ~\$1.00 per pound of salt required by the TES.

We therefore selected salts (based on prices quoted in the Chemical Marketing Reporter) costing up to \$3/lb which could be used either in the pure state or in eutectic mixtures. Economic constrictions also required that candidate PCM's be compatible with low carbon or stainless steels, since more corrosion resistant metals such as Hastelloy and Inconel would price the system beyond acceptable levels.

This resulted in a compilation of 174 pure salts costing less than \$3/lb. This list was then further screened to eliminate salts which are unacceptable due to corrosiveness, potential decomposition, or other limitations that prevent a TES design life of 30 years. It was concluded that salts within the chloride, carbonate, hydroxide and nitrate generic families are acceptable. Eutectics of each of these salts were selected that are in the desired price range, compatible with stainless steel alloys, and will not decompose over the life of the equipment.

Each of these salts must, however, be purified beyond commercial standards in order to exhibit desired corrosion characteristics. It was determined that moisture is the major impurity that must be eliminated, and it will probably be necessary to dry the salts in the heat exchanger modules after fabrication using a vacuum-freeze-thaw or similar process.

Pure chlorides are generally characterized by high melting points, low toxicity and no significant vapor pressure up to $\sim 800^{\circ}\text{C}$ (1475°F). They are available in quantity and generally inexpensive. Available thermo/physical/chemical data indicated that they have good potential for PCM applications and form eutectics that operate at a high temperature range of $320^{\circ}\text{--}540^{\circ}\text{C}$ ($600\text{--}1000^{\circ}\text{F}$).

Chloride eutectics in general exhibit thermal stability and long cycle life. The eutectics cost approximately \$.05/lb. Although little corrosion data was obtained for long-term exposure of metals in molten chloride environments, it was generally agreed that purified molten chlorides can be contained in mild steel. If purification is to be performed on-site, zone purification of the molten salt in a smaller separate holding chamber prior to adding the PCM to the TES vessel is recommended.

Of the inorganic hydroxides, sodium hydroxide is available in bulk quantities and is relatively inexpensive (\$.20/lb). It was identified as the major component of "Thermkeep," the salt found in a commercially available moderate temperature storage system ($500\text{--}600^{\circ}\text{F}$). The atmosphere above this salt must be inert, dry and free of CO_2 .

Nitrates/nitrites exhibit low melting points and relatively low heats of fusion. A system has been described (Reference 2) using potassium nitrate, sodium nitrate, and sodium nitrite. By varying the percentages of all three, eutectics in the $285\text{--}655^{\circ}\text{F}$ range have been obtained. Relatively complete thermal, physical and chemical corrosion data has been obtained and documented. These eutectics have a heat of fusion of about 35 BTU/lb, negligible corrosion on ordinary carbon steel at temperatures up to 1000°F , and are relatively inexpensive ($\sim$ \$.14/lb).

Virtually no breakdown or contamination should be expected if the molten salt is operated in an inert, dry atmosphere. It is recommended that the nitrate/nitrite systems be utilized in the moderate temperature range ($300\text{--}600^{\circ}\text{F}$). Work performed by Kirst, et al (Reference 3), showed that open hearth steel can be used with nitrate/nitrites up to 850°F . At temperatures from $850\text{--}1100^{\circ}\text{F}$, high chromium nickel steels and certain low chromium alloys containing aluminum and silicon are recommended.

3.2 CONTAINMENT, SAFETY AND HANDLING CONSIDERATIONS

Authorities generally agree that even if present in minute amounts, water can cause excessive corrosion with chloride salts. Littlewood (References 4 and 5), Koger (Reference 6), Susskind (Reference 7) and DeVan (Reference 8) support the hypothesis that molten chlorides can be contained in mild steel if they are dry and pure. Susskind tested a eutectic of NaCl/KCl/MgCl₂ in 1020 mild steel for 1000 hours at 500°C (915°F) and noted no intergranular or mass transfer corrosion. The penetration depth was .7 mils/yr. It should be pointed out that extreme material preparation care was taken. All apparatus in which salts were prepared were thoroughly cleaned and leak tested. Inert atmospheres of helium or argon were used and these were purified by passage over titanium chips at 850°C. The eutectic was prepared by vacuum-melting and outgassing at 500°C to a pressure of less than 20 μ . Reagent grade salts and anhydrous MgCl₂ were used. Reference 9 reports successful containment of chlorides after removal of water by using a gettering metal (aluminum or magnesium). Obviously, if such strict purification standards must be met, it will materially increase the PCM cost.

MgCl₂ and CaCl₂, when strongly heated, give off toxic fumes which can be a problem if a TES unit ruptures. Also, chlorides have a very large volume change on fusion; for example for NaCl the volume change from solid to liquid is 25%, so that significant salt movement will occur during cycling. CaCl₂ is a desiccant, so that an exothermic reaction will occur if it contacts water. Chlorides should be operated under a dry N₂ atmosphere. Mg(OH)₂ contamination of MgCl₂ results in the formation of oxichloride cement (MgOCl), which can be a problem.

Two contaminants which pose a corrosion problem in NaOH are H₂O and CO₂, which can be absorbed from the atmosphere. Use of a blanket atmosphere is essential and References 9 and 10 agree it should be H₂. Reference 9 notes that this introduces possible long-term problems with hydrogen embrittlement of the alloys and weldments of the containment unit. Noting the danger of explosion inherent in a pressurized H₂ atmosphere, Reference 10 suggests that satisfactory results might be obtained using a mixture of 10% H₂ and 90% N₂, which would reduce risk. Reference 11 questioned the seriousness of CO₂ contamination and pointed out some contradictions in existing data regarding water contamination. Although most authorities suggest using stainless steel, Comstock and Wescott use mild steel in their "Thermkeep" system, apparently made possible by the use of a corrosion inhibitor. Corrosion problems may be expected to be worse for KOH than NaOH (Reference 11).

Hydroxides are extremely hygroscopic and any contact with water will cause a highly exothermic reaction (possibly explosive in nature). In addition, hydroxides are caustic and can be dangerous to personnel in the vicinity of a ruptured container. According to Reference 12, NaOH may give off toxic fumes when strongly heated.

Nitrates/nitrites are superior to most salts investigated. They form a passivating layer on steels by the formation of surface oxide layers. Moreover, the presence of small amounts of water does not appear to increase the corrosion rate significantly (Reference 8).

Nitrates do not pose some of the hazards associated with other salts; they evolve no toxic gases nor are they caustic. They should, however, be kept out of contact with organic matter (fire hazard), cyanide and aluminum. At temperatures above 454°C (840°F), nitrites continuously degrade ($5\text{NaNO}_2 \rightarrow 3\text{NaNO}_3 + \text{Na}_2\text{O} + \text{N}_2$). This represents the upper limit to which these salts are useful and care should be taken to prevent nitrite containing TES units from overheating. Baker Chemical lists the decomposition point of NaNO_3 as 380°C (715°F). Compared to chlorides, nitrates present less problem from volume change on fusion; the increase for NaNO_3 is 10.7%, that for KNO_3 only 3.3% and that for NaNO_2 less than 20% (Reference 13).

3.3 SELECTION MATRIX

Based on our evaluations, Figure 3-1 presents a list of selected salts and salt eutectics which cover the temperature range from 142 to 504°C (287 to 939°F). In addition to melting point data, the key thermal properties required for system sizing are given; i. e., the latent heat of fusion (ΔH_{fs}), solid and liquid specific heat (c_{ps} and c_{pl}), thermal conductivity (k_s , k_l) and density (ρ_s and ρ_l). It should be noted, however, that the property data listed is in many instances based on analytical techniques and are the only data available for design purposes. Further experimental studies are required to accurately define salt properties. This information is sufficiently accurate, however, for the preliminary assessment of latent heat TES concepts. Figure 3-2 gives a preliminary assessment of salt costs, including purification.

SALT ELEMENT A B C	MELT POINT C (F)	COMPOSITION WEIGHT %			HEAT OF FUSION CAL/GM (BTU/LB)	H ₁₉	SPECIFIC HEAT CAL/GM °C		THERMAL CONDUCTIVITY 10 ⁻³ X CAL/SEC °C CM (BTU/HR FT °F)		DENSITY GM/CC (LB/FT ³)	
		A	B	C			SOLID (C _{ps})	LIQUID (C _{pl})	SOLID (K _s)	LIQUID (K _l)	SOLID (G _s)	LIQUID (G _l)
KNO ₃ NaNO ₃ NaNO ₂	142 (287)	53	7	40	19.5 (35) ²		29	32 ²	1.36 ¹ (.33)	1.36 ² (.33)	1.97 ¹ (123)	1.97 ² (123)
KNO ₃ NaNO ₃ NaNO ₂	179 (354)	PARTHERM		350	19.5 (35)		29	32	1.36 ¹ (.33)	1.36 (.33)	1.97 ¹ (123)	1.97 ² (123)
Ca(NO ₃) ₂ NaNO ₂	204 (399)	48.3	51.7		31.2 (56)		33	36	1.70 ¹ (.411)	1.70 ² (.411)	2.34 ¹ (146)	2.34 ² (146)
NaNO ₃ KNO ₃	220 (428)	45.7	54.3		32.8 (58.8)		36	36	1.17 ² (.28)	1.3 ² (.33)	2.18 ¹ (136)	1.88 ² (117)
NaNO ₃ NaOH	246 (475)	84.5	15.5		42.6 (76.5)		45	45	1.56 ¹ (.377)	1.56 (.377)	2.24 ¹ (140)	1.933 ² (120.7)
NaCl NaNO ₃	237 (567)	4.6	95.4		46.8 (84)		44	43	1.46 ¹ (.35)	1.46 (.35)	2.21 ¹ (141)	1.88 ² (117)
NaNO ₃	307 (585)	100			43.5 (78.1) ²		45 ²	44 ²	1.35 ² (.33)	1.45 ² (.35)	2.26 ² (141)	1.90 ² (119)
NaOH	318 (605)	100			76 (176)		44 ²	50 ²	2.20 ¹ (.53)	2.20 ² (.53)	2.83 ¹ (180)	1.76 ² (108)
KCl KNO ₃	320 (608)	4.5	95.5		26.21 (47)		23	29	1.15 ¹ (.278)	1.15 (.278)	2.11 ¹ (132)	1.85 ² (116)
KOH	360 (680)	100			32.1 (57.6)		32	36 ²	2.20 ¹ (.53)	2.20 ² (.53)	2.94 ¹ (177)	1.73 ² (108)
KCl NaCl MgCl ₂	385 (725)	14.5	22.3	63.2	110 (197)		23	248	1.6 (3.8) (.87 (92))	1.9 (2.4) (.47 (59))	2.25 ¹ (140)	1.63 ² (102)
NaCl BaCl ₂ MgCl ₂	418 (784)	28.4	31.8	39.8	81.6 (146)		19	21	1.6 (3.8) (.87 (92))	1.9 (2.4) (.47 (59))	2.76 ¹ (172)	2.12 ² (132)
NaCl MgCl ₂	450 (842)	60	40		111 (199)		22	24	1.6 (3.8) (.87 (92))	2.27 (.55)	2.23 ¹ (139.1)	1.61 ² (100)
CaCl ₂ KCl NaCl	465 (869)	64.5	6.5	29	77.6 (139)		21	23	1.6 (3.8) (.87 (92))	1.9 (2.4) (.47 (59))	2.15 ¹ (134)	1.85 ² (115)
NaCl CaCl ₂	500 (978)	33	67		67 (121)		20	24	1.6 (3.8) (.87 (92))	2.44 (.59)	2.16 ¹ (134)	1.89 ² (118)
KCl NaCl CaCl ₂	544 (1071)	5	29	66	67 (120)		26	24	1.6 (3.8) (.87 (92))	2.39 (.58)	2.15 ¹ (134)	1.90 ² (119)

- 1) DUE TO LACK OF INFORMATION, VALUE LISTED FOR SOLID IS SAME AS AVAILABLE FOR LIQUID
2) EXPERIMENTAL DATA

Fig. 3-1 Thermophysical Property Data of Selected Salts

SALTS	BULK PRICES		QUANTITY COST CORRECTED FOR WATER CONTENT	TOTAL COST INCL \$.05/LB FOR WATER, O ₂ , AND SOLID IM- PURITIES REMOVED
	CHEMICAL MARKETING REPORTER (7 - 19 - 76)	MANUFACTURER'S TRUCKLOAD > 20,000 LB		
MgCl ₂ · 6 H ₂ O	.1275	.0850	.255/.170	.305
CaCl ₂ · H ₂ O	.0275	.0440	.035/.055	.105
NaCl	.02	.0177	—	.07
KCl	.02	.0755	—	.1255
NaNO ₂	—	.3095	—	.3595
NaNO ₃	.065	.1095	—	.1595
KNO ₃	.095	.1825	—	.2350
NaOH	.25	.143	—	.193
KOH	.075	.22	—	.27
BaCl ₂	.155	—	—	.205
Ca(NO ₃) ₂	—	.1175	—	.1675
U-TEC-TIC*	—	.30	—	.35

*U-TEC-TIC = HITEC/HTS/PARTHERM

Fig. 3-2 Cost Estimates — Salts Recommended for TES Systems

SECTION 4

ALTERNATE HEAT EXCHANGER CONCEPTS

A number of alternate TES heat exchanger concepts may be considered, including: standard tube/shell, intermediate pumped metal loop, heat pipe, rotating drum and macro- and micro-encapsulated PCM designs. A preliminary review of these designs indicated that the standard tube/shell and intermediate pumped metal loop designs offer the most potential for near-term implementation.

Figure 4-1 illustrates the tube/shell design. This unit closely resembles standard heat exchanger units. As shown, the fluid to be heated or cooled flows through tubes which are surrounded by the PCM (salt) mass. The tubes will be placed on hexagonal centers for tight packing. Since the salt will occupy greater volume in the liquid than solid state ($\rho_l < \rho_s$), during energy storage the hot fluid will enter the top of the unit and exit at the bottom. Conversely, during energy usage the fluid to be heated will enter at the bottom of the unit and exit at the top. This will assure that solidification will proceed from the bottom up, avoiding the formation of voids. Salt quantity will be specified such that space for a dry inert gas over-blanket will remain. Since the salt will possess relatively low vapor pressure, shell thickness will not be excessive. The potentially high pressure working fluid will be contained within the small diameter tubes.

The intermediate pumped metal loop system shown in Figure 4-2 uses a similar heat exchanger design, with the difference that the liquid metal such as sodium or NaK is used to transport energy to or from the individual modules. Depending on design considerations, individual modules may be connected in series, parallel and a parallel-series combination.

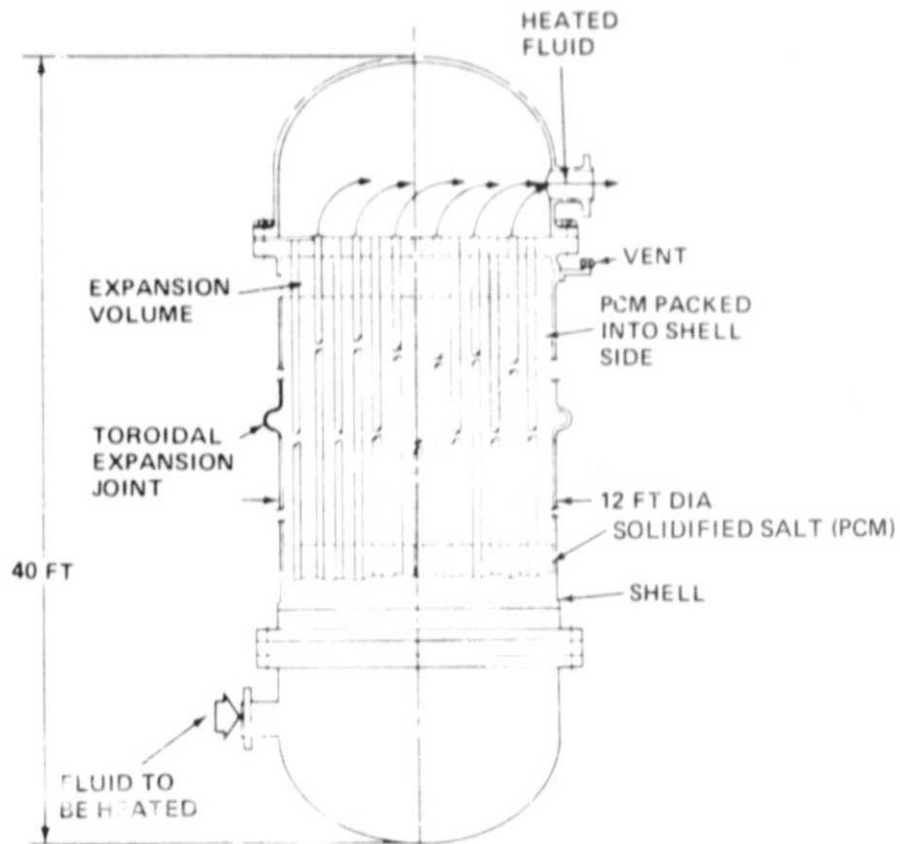
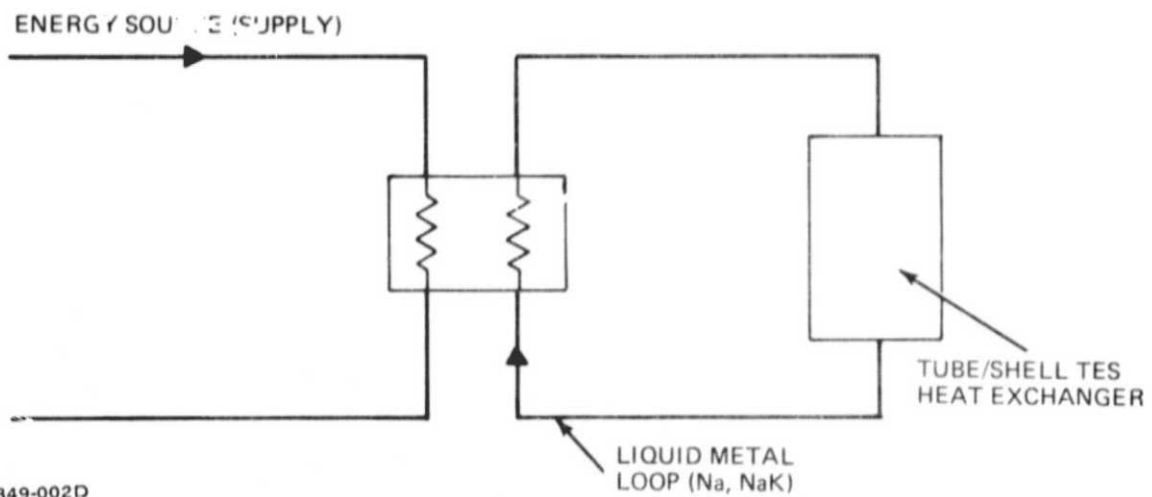


Fig. 4-1 TES Shell and Tube Heat Exchanger Concept



2349-002D

Fig. 4-2 Intermediate Pumped Metal Loop Concept

SECTION 5

HEAT EXCHANGER SIZING

5.1 SALT QUANTITY REQUIREMENTS

To select a salt for a given application, a temperature level must be chosen for the available energy. Salts must be chosen which allow sufficient temperature differences (ΔT) between the fluid flow temperature and the salt melt temperature. The cheapest salt for energy stored per unit cost should be chosen. The total energy percentage which can be stored in each salt can be found directly from the salt melt temperature and given fluid conditions.

For shell and tube designs, energy will be stored as both sensible and latent heat. To estimate the total mass of salt needed, therefore, both sensible and latent heat contributions must be taken into account. This requires an estimate of the salt temperature profile at the end of the usage period and at the end of the storage period. A general procedure to determine the mass of salt required is summarized below:

- (1) Select the salt or salts, and percentage of total energy stored in each salt, using inlet and outlet temperatures, and enthalpies.
- (2) Determine the "average" salt temperature, accounting for gradients both parallel and perpendicular to the fluid flow lines at the end of the storage and usage periods. At the end of the storage period, the average liquid temperature, T_{ℓ} , of the salt may be approximated by:

$$T_{\ell} = \left(\frac{T_{fi} + T_{fo}}{2} \right) - \frac{(\Delta T)_{\min}}{2} \quad (5-1)$$

where $(\Delta T)_{\min} = T_{fo} - T_m$

and T_{fi} = fluid inlet temperature

T_{fo} = fluid outlet temperature

T_m = salt melt temperature

Similarly, at the end of the usage cycle, the average solid temperature, T_s , of the salt may be approximated by

$$T_s = \left(\frac{T_{fi} + T_{fo}}{2} \right) + \frac{(\Delta T)_{\min}}{2} \quad (5-2)$$

when $(\Delta T)_{\min} = T_m - T_{fo}$

- (3) Calculate total available latent and sensible storage capacities for each salt as follows:

$$Q_{\text{available}} = \Delta H_{fs} + c_{p,s} (T_m - T_s) + c_{p,l} (T_l - T_m) \quad (5-3)$$

where

T_m = salt melt temperature

T_s = average solid salt temperature at end of usage period

T_l = average liquid salt temperature at end of storage period

$c_{p,s}, c_{p,l}$ = solid and liquid salt specific heats

ΔH_{fs} = Salt Latent Heat of Fusion

- (4) Using this expression and the foregoing analytical procedure, the total mass of salt (or salts) required can be determined. This will be clearly demonstrated in the illustrative example discussed in Section 8.

5.2 TUBE QUANTITY AND SPACING

To calculate the length, spacing and required number of tubes, various factors must be considered, including:

- Inside and outside tube diameter
- Maximum module diameter
- Fluid conditions
- Salt properties

In general, to determine tube requirements an iterative calculation procedure will be necessary which considers both storage and usage phases.

Equations which describe heat flow in and out of a pipe surrounded by a salt are given by several standard heat transfer expressions. Considering simple one-dimensional heat transfer expressions, neglecting heat capacity of the salt, the freezing energy flux per unit length of pipe may be written:

$$\frac{\dot{Q}}{L} = \left[\frac{2 \pi k_s}{\ln\left(\frac{R}{r_o}\right)} \right] (T_w - T_m) \quad (5-4)$$

where,

k_s = solid state salt thermal conductivity, BTU/hr-FT-°F.

T_w = pipe outside wall temperature, °F

T_m = salt melting point, °F

r_o = pipe outer radius, feet

R = salt melt radius, feet

L = total required length of pipe, feet

This may also be expressed in terms of fluid side film coefficient and pipe wall thermal resistance as:

$$\frac{\dot{Q}}{L} = 2\pi \left\{ \frac{1}{\left(\frac{1}{hr_i}\right) + \frac{\ell \ln(r_o/r_i)}{k_w}} \right\} (T_f - T_w) \quad (5-5)$$

where,

h = fluid film coefficient, BTU/hr ft² °F

r_i = pipe inner radius, feet

r_o = pipe outer radius, feet

k_w = pipe wall thermal conductivity, BTU/hr ft °F

T_f = fluid bulk temperature, °F

T_w = pipe outer wall temperature, °F

Energy stored in the salt is then:

$$\int \frac{\dot{Q}}{L} dt = \Delta H_{fs} \rho_s \pi (R^2 - r_o^2) \quad (5-6)$$

Integrating this expression after eliminating T_w using 5-4 and 5-5 and substituting for $\dot{Q}/L$ in 5-6 in terms of T_f and T_m gives:

$$\left(\frac{R}{r_o}\right)^2 \ell \ln\left(\frac{R}{r_o}\right)^2 + \left[\left(\frac{R}{r_o}\right)^2 - 1\right] \left\{ \frac{2k_s}{r_i} \left[\frac{1}{h} + \frac{r_i}{k_w} \ell \ln\left(\frac{r_o}{r_i}\right) \right] - 1 \right\} = \frac{(T_f - T_m) 4 tk_s}{\Delta H_{fs} \rho_s r_o^2} \quad (5-7)$$

which describes the relationship between active time, t , pipe spacing, temperature difference and film coefficient

Internal film coefficients for the working fluid may be calculated using standard heat transfer expressions. For the tube/shell design with steam or pressurized water as the energy source or sink, the internal film coefficient may be calculated using the following expression (Reference 13):

$$h = 0.0243 \left(\frac{k_f}{D} \right) \left(\frac{\rho_f V D}{\mu} \right)^{0.8} (P_r)^{0.4} = X_1 V^{0.8} \quad (5-8)$$

where: k_f = fluid conductivity
 ρ_f = fluid density
 X_1 = constant

Similarly, for the pumped metal loop system the internal heat transfer coefficient may be calculated (Reference 14) using:

$$h = \left(\frac{k}{D} \right) \left[6.7 + 0.0041 (R_e P_r)^{0.793} (e)^{41.8 P_r} \right] \quad (5-9)$$

where R_e = Reynolds number, P_r = Prandtl number and the internal velocity is:

$$V = \left(\frac{\dot{M}}{N \rho_f} \right) \frac{1}{\pi r_i^2} = \frac{X_2}{N} \quad (5-10)$$

where $\dot{M}$ = fluid mass flow rate
 ρ_f = fluid density
 N = number of pipes
 X_2 = constant

Note that the liquid density used in this comparison is somewhat conservative. Calculation of the liquid-solid interface movement is based on solid density (equation 5-7), but some allowance must be made for lowering the level of PCM in the module as the solid fraction increases, since this reduces the active length of the individual pipes, or:

$$N = \frac{M_s}{L \rho_l \pi (R^2 - r_o^2)} = \frac{X_3}{L (R^2 - r_o^2)} \quad (5-11)$$

where M_s = salt mass
 ρ_l = salt liquid density
 X_3 = constant

For the tube and shell case, equations 5-8 through 5-11 may be used to size the system once the pipe and wall thickness has been determined from pressure containment and corrosion considerations. Considering pipes on hexagonal centers (see Figure 5-1), a TES module diameter can be estimated from the total cross-sectional area per pipe as follows:

$$D_m = 2 \sqrt{N (2R)^2 \left(\frac{\sin 60}{\pi} \right)} \quad (5-12)$$

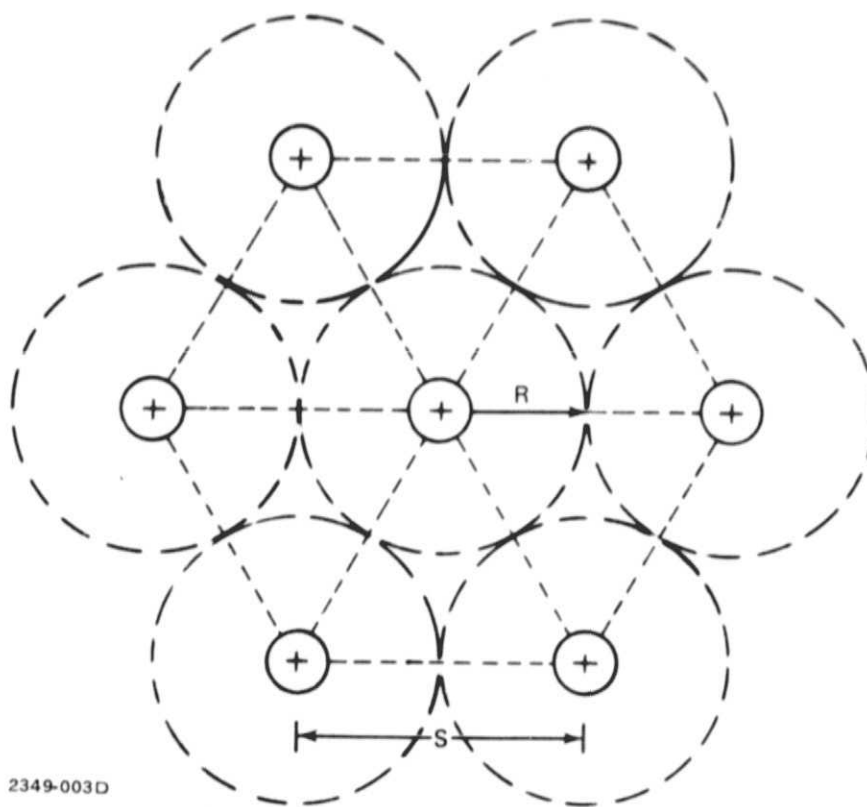


Fig. 5-1 Hexagonal Arrangement of Heat Pipes in Cannister

Next, considering the energy storage and usage we may develop an expression for pipe spacing as a function of pipe OD and the number of pipes by combining expressions. During energy storage the following expression must be solved:

$$\left(\frac{R}{r_o}\right)^2 \ln \left(\frac{R}{r_o}\right)^2 + \left[\left(\frac{R}{r_o}\right)^2 - 1\right] \left[\left(\frac{N}{C_1}\right)^{0.8} - C_2\right] = C_3 \quad (5-13)$$

where:

$$C_1 = \frac{r_i X_1 X_2^{0.8}}{2 k_s}$$

$$C_2 = \frac{2 k_s}{k_w} \ln \left(\frac{r_o}{r_i}\right) - 1$$

$$C_3 = \frac{(T_f - T_m) 4tk_s}{\Delta H_{fs} \rho_s r_o^2}$$

A similar expression for the energy usage period may be written.

This leaves us with three equations (5-11, 5-12 and 5-13) and three unknowns (N, L and R), permitting a separate solution for these parameters during energy storage and usage. Obviously, the design should be based on worse-case results (i.e., during usage or storage) and the minimum tube spacing should be used in sizing the TES modules.

5.3 MODULE SIZING

The trade-off between number and size of individual TES modules must be based on space, handling and transportation considerations. In many applications, such as for our power plant study, space will not be as important as the latter parameters. The TES modules should be fabricated in a factory environment. Quality control must be maintained at high level to produce a leak-tight structure. Helium leak checks, and X-ray photos should be made of all welds; and records of inspections maintained on file. Each TES module should be flushed with purified salt. The TES module is then backfilled with pressurized, dry inert gas and the salt cleaned to remove impurities picked up in the flushing process.

The prefabricated modules are shipped to the site where the necessary piping, valves and controls are assembled to construct the total TES system. Based on standard railroad car shipping and handling considerations, a maximum TES module size of 15 feet diameter by 40 feet long is recommended.

SECTION 6

CONTROLS

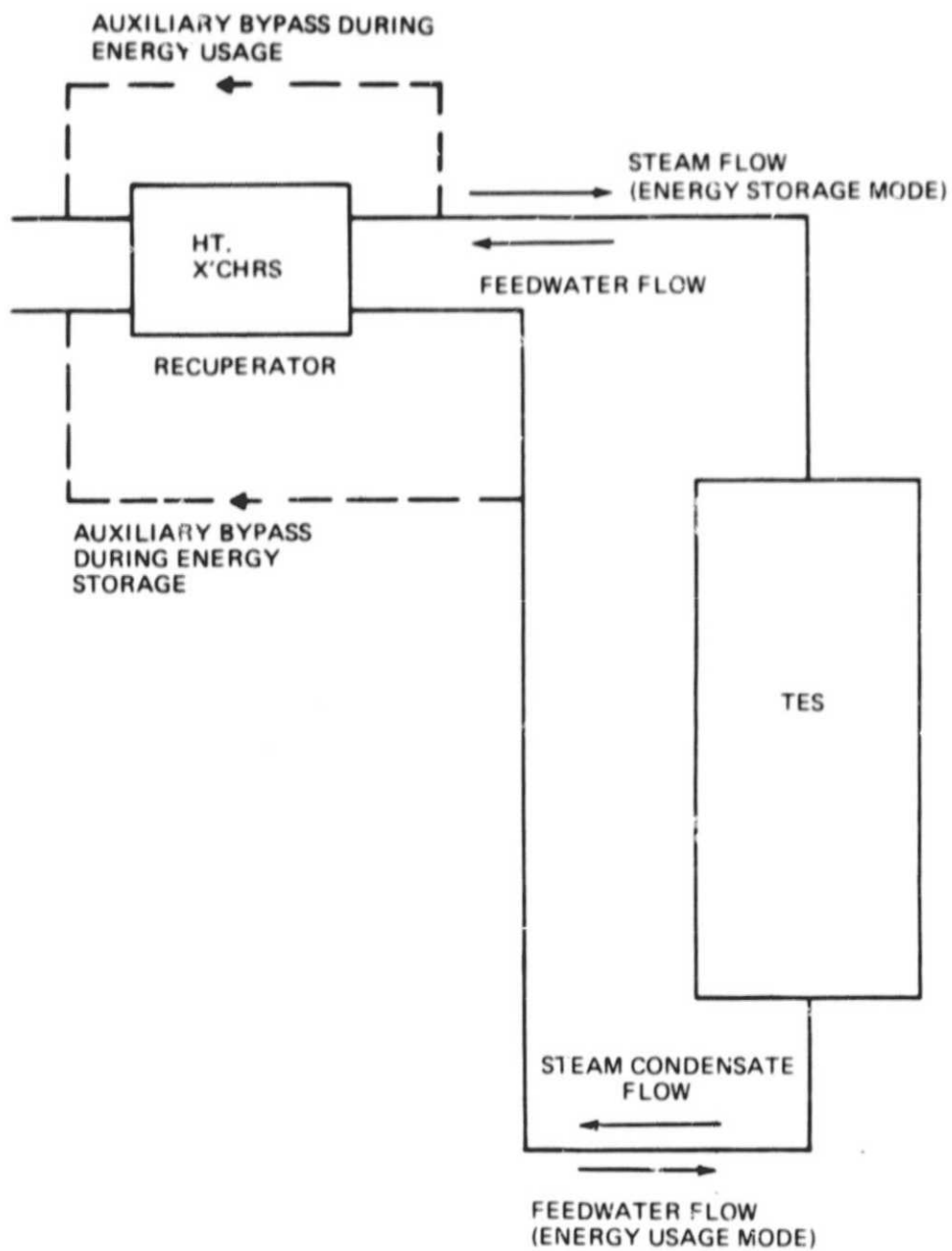
The controls necessary for the integration of the TES into a system are divided into two categories. First, controls necessary for normal system operation, and second, those necessary for safety.

For TES use during normal system operation, major control categories can be divided into flow control and unit monitoring. Flow control can be accomplished by various pressure, flow and liquid level control valves. These control valves must have built-in logic so that they operate automatically. Also, control should be incorporated so that operators will be able to override any valve if a situation warrants.

Positive shut-off valves also provide for isolation of individual TES units or strings, so that TES units can be removed from service. These operate on signal if the heat exchangers become over-pressurized as in the event of a tube failure. These must also have override control to isolate TES units.

Unit monitoring will be accomplished by integrating all valve signals into a micro-processor and then tying this unit into the main control system. It will incorporate signals to show normal operating and faulted conditions. Redundancy can be provided if the hazards posed by a TES malfunction are considered great enough to warrant it.

Since the salt temperature will vary with time, it will be necessary to bypass the flow and/or use a recuperator to maintain the thermodynamic integration of TES with the power conversion system. For example, a recuperator system (Figure 6-1) could be used to compensate for the variation in heat exchanger effectiveness with time.



2349-004D

Fig. 6-1 TES Control System – Utility Application

SECTION 7

TOTAL TES SYSTEM COSTS

In order to compare a latent heat TES design to other options, an economic evaluation will be required. This analysis must be performed after alternate designs have at least initially been defined, so that all of the component costs can be included. Many designers discuss thermal energy storage costs by considering only the salt and its cannister. Peripheral items, however, such as land, controls, piping and valving, engineering, construction fees, etc. can easily result in a total system cost which is two or three times higher than the "storage cost" taken by itself.

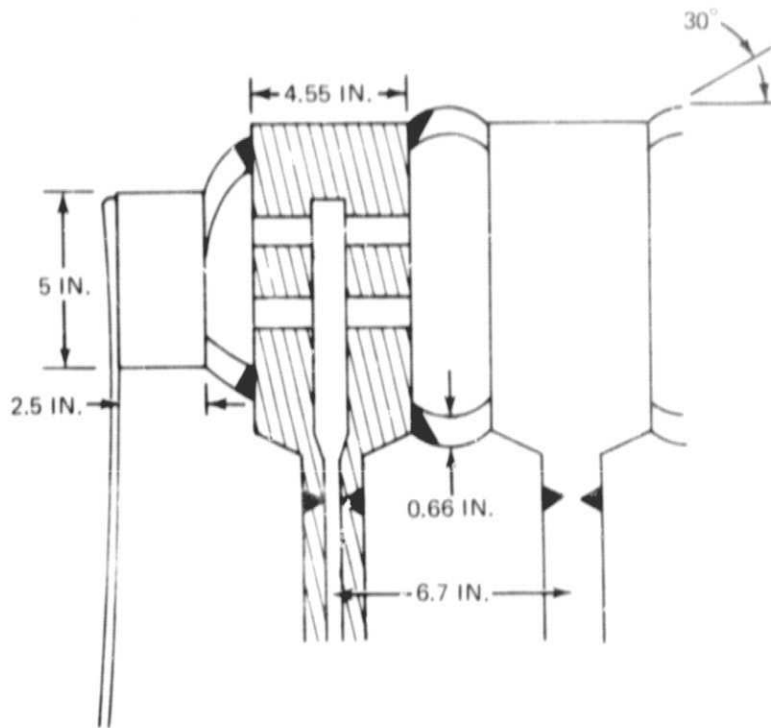
7.1 SALT

The first cost item to be considered is that of the PCM material. Using the technique discussed in Section 4, a salt or salts may be selected and the total required mass computed. The total salt cost must include an estimate of the added purification required and can be calculated using the unit costs presented in Figure 3-2.

7.2 HEAT EXCHANGER

The heat exchanger cost will be a direct function of the operational temperature and pressure levels of the unit, as well as its design. Feedwater heaters which normally operate at relatively high pressures (up to 4000 psi) and low temperature levels (100 to 500° F) cost in the range of \$15/ft² of heat transfer area. TES applications requiring higher temperature levels (750 to 1000° F) and smaller tube density, will cost significantly more, however. The combination of higher pressure and temperature as well as salt corrosion dictate the use of stainless steel for TES modules, further increasing construction costs. For example, we estimate that a conventionally designed tube/shell TES module for a typical feedwater heating application (4300 psi, 1000° F) will cost between \$90 and \$120/ft² of heat transfer area. Note that as part of our study (Reference 1), a stayed heat exchanger design (Figure 7-1) was developed, lowering the module cost to about \$50/ft² of heat transfer area.

With the stayed design, a cost of \$390,000 was estimated for one 12 ft. diameter by 40 ft. long stayed dome TES module operating at 4300 psi and 1000° F, totally built of 321 stainless steel. As a first-cut, a designer may ratio this cost by the inverse of the diameter squared (D_m^{-2}) in order to estimate a similar, but smaller diameter unit.



2349-005D

Fig. 7-1 Stayed Configuration Tube and Shell Heat Exchanger

7.3 CONTROLS AND PIPING COSTS

Integrating the TES modules into an existing or new facility requires additional controls and piping costs. These costs are difficult to estimate and must be evaluated based on preliminary system layouts incorporating the TES design. As a reference for a TES feedwater heating application, controls, piping and valving accounted for about 10% of the total system cost (see Section 8).

7.4 TOTAL INSTALLED COST

In addition to the above costs, the designer must consider peripheral costs, such as: land, grading, roads and paving, foundations, interest during construction, and engineering and construction fees. Based on various power plant installations, the following unit cost data can be used for preliminary economic evaluations:

● earthwork and grading	\$16,375/acre
● roads and paving	\$5.38/yd ²
● land and land rights	\$100,000/acre
● foundations	\$2.66/yd ³

Typically, power plant designers add a contingency and interest cost of 15% during construction and an engineering and construction management cost of 12% (see Section 8). Although these factors may vary depending on the application, they are representative figures for preliminary evaluations.

Obviously, not all of the above costs may be incurred in a given application. However, since they can significantly impact overall system trade-offs, it is important that the designer compare the total expense of the TES system to the total expense of his alternative.

SECTION 8

ILLUSTRATIVE EXAMPLE

This section presents the significant design calculations to size a TES system for a typical application, i.e., to augment power plant feedwater heating. A more thorough description of requirements (controls, valves, etc.) is presented in Reference 1. Relevant system design data are presented in Figure 8-1.

As explained earlier, in order to choose salts, it is necessary to know at what temperature energy is provided. Figure 8-2 shows the flow stream temperatures as a function of percent of total energy for storage and usage temperatures. In the case of feedwater heating, it can be seen that 33% of the total energy will be stored in the higher temperature salt and 67% in the lower temperature salt. As shown in Figure 8-3, the total amount of energy stored in each salt is then:

KCl NaCl MgCl ₂	4.35 x 10 ⁸ BTU
NaCl NaNO ₃	8.83 x 10 ⁸ BTU

which will require the following salt quantities:

KCl NaCl MgCl ₂	1.68 x 10 ⁶ lbs.
NaCl NaNO ₃	5.32 x 10 ⁶ lbs.

For the remainder of this example we shall confine ourselves to the high temperature salt, since the procedure for the low temperature salt is identical.

Strictly as a first-cut assumption, we used 1" ID tubes in our design. For this tube ID, it was determined from pressure considerations that a .18" wall thickness would be more than adequate and also provide allowance for corrosion, i.e.:

$$\text{Thickness} = Pr/Y.S. = 4323 \text{ psi} \times .5"/14,000 = .154"$$

P = Operating Steam Pressure

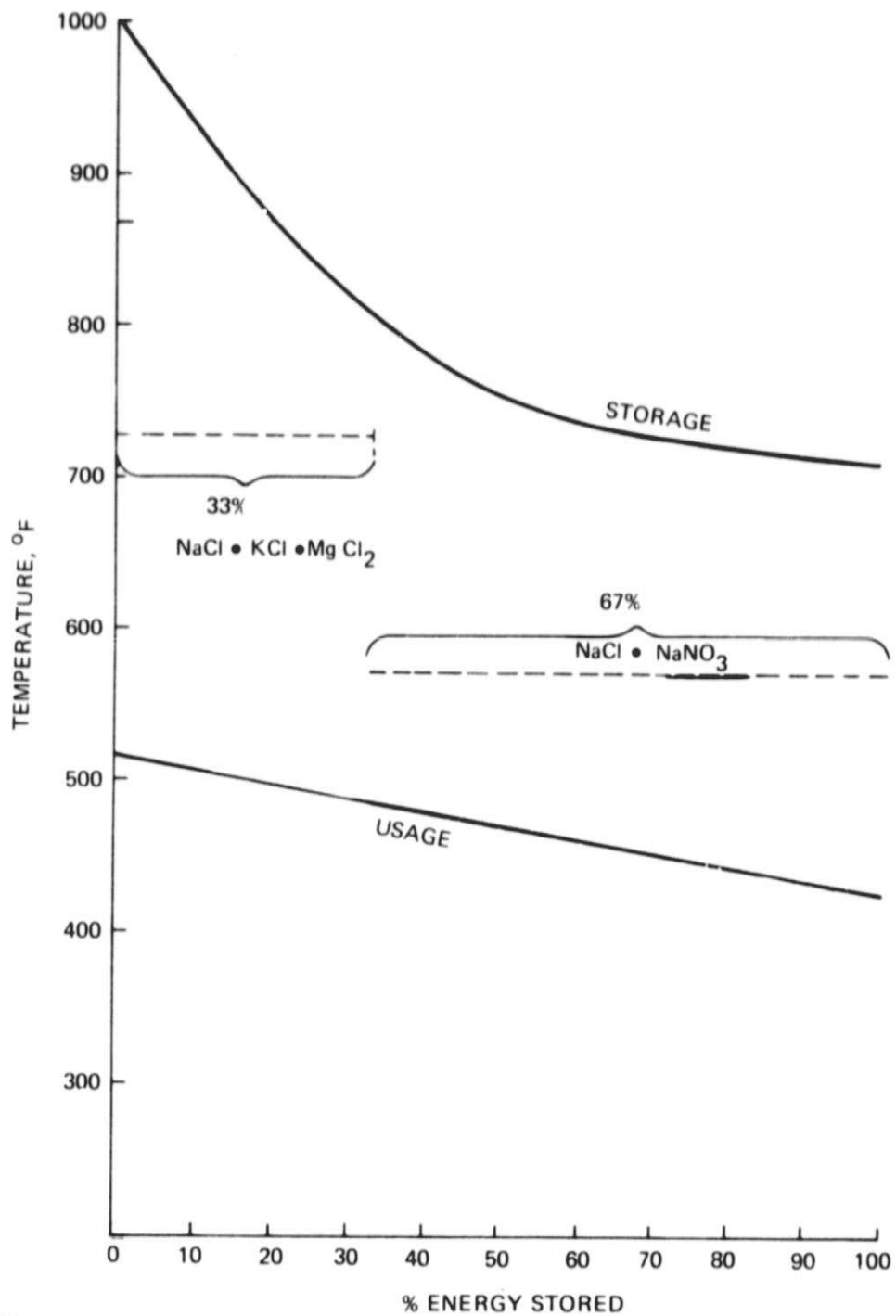
r = Tube Radius

Y.S. = Yield Stress

FORT MARTIN PLANT	
FEEDWATER HEATING	
<u>Storage (18 Hours)</u>	
Inlet Temperature, ° F	1,000
Outlet Temperature, ° F	705
Inlet Pressure, psi	3,500
Outlet Pressure, psi	3,200
Inlet Enthalpy, BTU/lb	1,421.7
Outlet Enthalpy, BTU/lb	875.5
Flow Rate, lbm/hr	134,162
<u>Usage (6 Hours)</u>	
Inlet Temperature, ° F	423.4
Outlet Temperature, ° F	514.4
Inlet Pressure, psi	4,323
Outlet Pressure, psi	4,323
Inlet Enthalpy, BTU/lb	404.8
Outlet Enthalpy, BTU/lb	504.0
Flow Rate, lbm/hr	2,217,000
Total Energy Stored, BTU:	1,319,000,000

2349-007D

**Figure 8-1 Fort Martin Feedwater Heating TES Application:
Fluid Conditions and Heat Balance Information**



2349-008D

Fig. 8-2 Energy Storage and Usage vs. Temperature Ft. Martin Plant, Feedwater Heating

Salts 1. NaCl KCl Mg Cl₂ Melt Point: 725°
2. NaCl NaNO₃ Melt Point: 567°

(A) Storage Mode

Steam in at 1000°F, 3500 psi, h = 1421.7 BTU/lbm

Water out at 705°F, 3200 psi, h = 875.5 BTU/lbm

Temperature range for each salt chosen to provide sufficient ΔT for heat transfer:

Salt 1: 1000° → 800°, 33% total energy
2: 800° → 705°, 67% total energy

(a) High Temperature Salt:

Salt 1: $\Delta T = 800^\circ - 725^\circ = 75^\circ F$

Average Flow Temperature: 900°F

Average Final Salt Temperature, $T =$

$$900 - 75/2 = 862.5$$

so that average sensible

component is $S = Cp \Delta T =$

$$.24 (862.5 - 725) = 33 \text{ BTU/lbm}$$

(b) Low Temperature Salt

Salt 2: $\Delta T = 705 - 567 = 138$

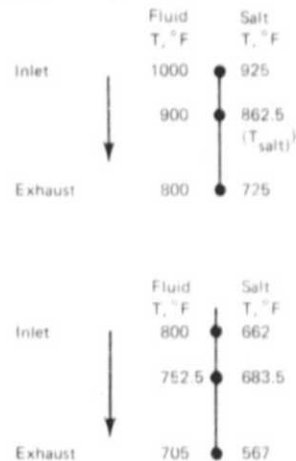
Average Flow Temperature = 752.5

Average Final Salt Temperature =

$$752.5 - 138/2 = 683.5$$

Average Sensible Component is

$$S = .44 (683.5 - 567) = 51.3 \text{ BTU/lbm}$$



(B) Usage Mode

Water in at 423°F, h = 404 BTU/lbm

Water out at 514.4°F, h = 504 BTU/lbm

67% split at 487°F

(a) High Temperature Salt

Salt 1: $\Delta T = 725 - 514.4 = 211^\circ F$

Average Flow Temperature = 500.5

Average Final Salt Temperature =

$$500.5 + 211/2 = 606.5$$

Sensible Component is $.24 (725 - 606)$

$$= 29.75 \text{ BTU/lbm}$$

(b) Low Temperature Salt

Salt 2: $T = 567 - 487 = 80^\circ F$

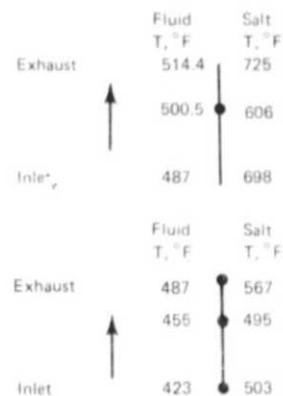
Average Flow Temperature = 455°F

Average Salt Temperature, $T =$

$$455 + 80/2 = 495^\circ F$$

Sensible Component = $.24 (567 - 495)$

$$= 31 \text{ BTU/lbm}$$



Total Available Energy Storage

Salt 1: Latent + Sensible = $197 + 33 + 29.75 = 254.8 \text{ BTU/lbm}$

Salt 2: Latent + Sensible = $84 + 51.3 + 31 = 166.3 \text{ BTU/lbm}$

(C) Salt Masses

$$\text{Total } Q = 1.319 \times 10^9 \text{ BTU}$$

$$33\% = 4.35 \times 10^8 \text{ BTU}$$

$$67\% = 8.83 \times 10^8 \text{ BTU}$$

$$\text{Salt 1: } = 1,679,500 \text{ lbm}$$

$$\text{Salt 2: } = 5,319,300 \text{ lbm}$$

2349-009D

Fig. 8-3 Salt Required for Shell/Tube and Heat Pipe Heat Exchanger Ft. Martin, Feedwater Heating Concept

First, consider the storage side. As the steam flow will cool from 1000° F to 800° F, properties are evaluated at 900° F as follows:

$$\rho_f = 5.2 \text{ lbm/ft}^3$$

$$\mu = .109 \text{ lbm/hr ft}$$

$$k_f = .04 \text{ BTU/hr ft}^\circ \text{F}$$

$$P_r = 2.7$$

$$D = 1.36 \text{ in} = 0.113 \text{ ft}$$

Total Flow Rate = 134, 162 lbm/hr, so Equation 5-8 becomes $h = .0495(V \cdot^8)$.

Equation 5-10 becomes $V = 4,730,414/N$.

On combining these expressions, we obtain $h = 10,827/N \cdot^8$

From Fig. 3-1, the following properties were used for the high temperature salt:

$$\Delta H_{fs} = 197 \text{ BTU/lbm}$$

$$\rho_s = 140 \text{ lbm/ft}^3$$

$$\rho_l = 102 \text{ lbm/ft}^3$$

$$k_s = .9 \text{ BTU/hr ft}^\circ \text{F}$$

so that Equation 5-13 becomes,

$$\left(\frac{R}{r_o}\right)^2 \ln \left(\frac{R}{r_o}\right)^2 + \left[\left(\frac{R}{r_o}\right)^2 - 1\right] \left[\frac{N \cdot^8}{425.6} - .97 \right] = 66.33 \quad (8-1)$$

Equation 5-11 for this case is $L = 5241.2/N(R^2 - .0032)$.

The above equation (8-1) uses the log mean average ΔT across the heat exchanger for $(T_f - T_m)$.

In a similar manner the equivalent of Equation 8-1 for the usage case can be calculated using water properties at 400° F:

$$\rho_f = 49 \text{ lbm/ft}^3$$

$$\mu = .26 \text{ lbm/hr ft}$$

$$k_f = .349 \text{ BTU/hr ft}^\circ \text{F}$$

$$P_r = .87$$

$$\text{Flow Rate} = 2,217,000 \text{ lbm/hr}$$

Equations 5-8 and 5-10 then become:

$$\begin{aligned}
 h &= .827 (V \cdot^8) \\
 V &= 8,295,000/N \\
 \text{or } h &= 283,517/N \cdot^8
 \end{aligned}$$

Using this and the same salt properties as before we get:

$$\begin{aligned}
 &\left(\frac{R}{r_o}\right)^2 \ln\left(\frac{R}{r_o}\right)^2 + \left[\left(\frac{R}{r_c}\right)^2 - 1\right] \left[\frac{N \cdot^8}{6563} - .97\right] \\
 &= 54.63
 \end{aligned}
 \tag{8-2}$$

The expression for the number of pipes (N, Equation 5-11) is the same for both cases.

Comparing Equation 8-1 and 8-2 it can be seen that since the term on the right of Equation 8-2 is smaller than the same term in Equation 8-1 and since the denominator under the $N \cdot^8$ term is larger, Equation 8-2 will give the smaller spacing. Therefore, the usage case dominates.

Examining Equation 8-2 it is apparent that since the factor of 6563 under $N \cdot^8$ is so large, N may vary over a large range without affecting the value of R significantly. Taking advantage of this we can estimate the value of R taking $N = 0$. For this case $(R/r_o)^2 = 24.2$ and $R = 3.345$ inches.

From Equation 5-12 for a 12 foot diameter this would require 423 tubes (N). Inserting this value of N in Equation 8-2 gives a value of $R = 3.336$ inches. The total length of tubing required, L, becomes $L = 167.3$ feet, which would make 5 modules having 33.5 feet active salt length leaving 6.5 feet for headers and vapor space.

A cost breakdown for this TES system is given in Figure 8-4 showing items of significant cost. Note that on a first cut basis the cost of the TES system was slightly less expensive than a comparable increase of plant capacity.

	<u>Cost</u>
Earthwork and Grading	\$ 8,200
Roads and Paving	1,300
Land and Land Rights	50,000
Foundations	93,000
Piping and Valving	1,166,800
Instrumentation and Control	50,000
Flash Tank	36,000
Recuperator	500,000
TES Units	7,800,000
TES Salt	<u>1,219,000</u>
Subtotal	\$10,924,300
Contingency & Int During Constr at 15%	1,638,650
Engrg & Constr Mgmt at 12%	1,310,920
Increm T-G (37.36MW) & Elect Cost at \$230/KW _e	<u>8,592,000</u>
Total	\$22,465,860
System Breakeven = (37.36 MW) (\$650/KW)	\$24,284,000
Net Savings — New Plant or Plant w/o Excess T-G	\$ 1,818,140
— Retrofit, Plant with Excess T-G	\$10,410,140

2349-010D

Fig. 8-4 Total TES System Cost, Ft. Martin Feedwater Heating Case

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